In the investigation described in the paper not all the specimens failed under plane strain, hence the reference to stress intensities as $K_Q$ values. These results are, however, accurate for the one thickness tested and conservative for thinner material. They may therefore still be used for quantitative comparison.

One of the major advantages of the linear elastic fracture mechanics approach is that, with a knowledge of operative stresses, critical defect sizes in real structures can be calculated from laboratory test results. The general formula is:

$$a = C\left(\frac{K}{\sigma}\right)^2$$

where $C$ is a constant and $\sigma$ is the applied stress.

The constant $C = 1/\pi$ for the most severe case of an infinitely sharp crack in an infinitely wide plate. Most practical cases will tolerate slightly larger defects than predicted by this formula. The residual stress operative in the heat-affected zone of a weld during postweld heat treatment will be the yield strength at the ageing temperature, $\sigma_y$ (not accounting for any physical stress raisers) and so defect sizes were calculated as:

$$\acute{a} = \frac{1}{\pi}\left[\frac{K_{Qi}}{\sigma_y}\right]^2$$

This parameter can be used as a susceptibility index to compare materials.

*References*


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# Technical Note: Fatigue Crack Propagation in Zircaloy-2 Weld Metal


BY D. A. FERRILL


During the course of an investigation into the mechanical behavior of Zircaloy weld metal, the fatigue crack propagation characteristics of the material were studied. This study was undertaken to gain insight into the growth characteristics of defects under cyclic loadings, since in service, this material would inevitably contain sources for crack initiation, such as structural discontinuties and weld defects.

The weld metal used in the investigation was obtained from full-scale laboratory mock-ups of typical weldments. The materials were welded in an evacuated and back-filled dry box using the gas tungsten-arc process; helium was used as the shielding gas. The as-welded material was chemically analyzed, and the results are shown in Table 1.

The weld metal studied was composed of large columnar beta grains that, on cooling, had transformed into colonies of lenticular alpha-prime ($\alpha'$)* grains. The material, having undergone melting and solidification, as well as the beta-alpha transformation upon cooling, exhibited a structure of typical Widmanstätten patterns. Figure 1 shows the weld metal microstructure. As seen in Fig. 1, the transformed alpha morphology consists of both massive-grain and platelet regions.

**Table 1—Weld Metal Chemical Analysis**

| | |
|---|---|
| $N_2$ | 15 ppm |
| $H_2$ | 15 ppm |
| $O_2$ | 1295 ppm |
| Fe | 1370 ppm |
| Cr | 965 ppm |
| Ni | 550 ppm |
| Sn | 1.42 wt-% |

The massive-grain regions are sheath-like, surrounding the prior beta grain boundaries. The platelet region, in the centers of the prior beta grains, was characterized by the $\alpha'$ grain size. The equivalent ASTM grain size (11.5) of these grains was determined by Hilliard's[1] intercept density technique under polarized light from contrast variations between individual platelet colonies.

The fatigue specimens were fabricated from all-weld metal sections. The specimens were machined as flat plates and subjected to cyclic bendin as cantilever beams under constan deflection loading. The test sections were of constant thickness (~0.100 in.) with the width linearly tapered so that the nominal longitudinal bending stress ($Mc/I$) did not vary over the length of the test section. Because of these conditions, the constant-deflection cycling was essentially constant-strain cycling, at least while the fatigue cracks were too small to significantly change the force-deflection characteristics of the specimen. The characteristics of this type of specimen have been described in more detail by Mowbray.[2]

Fig. 1—Weld metal microstructure. Polarized light. X100 (reduced 42% on reproduction)

The type of notch configuration employed in this fatigue investigation was a 0.014 in. diameter hole drilled through the specimen thickness in the center of the specimen at a point midway along the tapered gage length. This notch and specimen geometry produced a theoretical elastic bending stress concentration factor, $K_t$, of 2.80.[3]

The reason for selecting this type of notch configuration and size was to ensure that the nominal surface strain field at the notch section could be defined. Making the hole size small compared with the test-section width permitted one to assume that the nominal strain in all areas except those immediately adjacent to the defect prior to cracking was the same as that measured by strain gages mounted at a location removed a diameter or more from the hole. The fatigue testing was conducted in air at 600° F on a Krouse-type 150 lb constant-deflection


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* Alpha-prime ($\alpha'$) is the nomenclature given to the acicular structure that results from rapid cooling of zirconium alloys from a temperature in the beta-phase region $\gtrsim$ 1790° F (975° C) to a temperature in the alpha-phase region $\lesssim$ 1517° F (825° C).

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plate-bending machine modified to accept a three-zone, split-shell resistance furnace. Surface strain was measured during the first few cycles of each test using elevated temperature strain gages. The specimens were cycled at a rate of ~700 per minute.

It should be noted that since the primary emphasis in this investigation was placed on determining the conventional fatigue properties of the material, the specimens were designed for that purpose. The use of this specimen design and loading mode is not conducive to fundamental studies of crack propagation because of the difficulties associated with analysing and interpreting the varying strain field as the crack penetrates the specimen.

The crack propagation data collected during this investigation were obtained using visual measurements made with a × 20 telescope having a resolution of about 0.001 in. The measurements were made through a viewing port in the furnace on only the upper side of the specimens. Cycling was stopped while an observation was made.

For the type of specimens employed, initiation and propagation of cracks was limited to two positions on the hole periphery, thus restricting the area to be watched. Surface-crack length, load, and number of cycles, were recorded periodically during testing. Observations were performed approximately every 5–10% of life-to-specimen rupture.

Typical crack propagation data which were collected are shown in Fig. 2. These data are reported in cycles versus a normalized total surface crack length, obtained by dividing the total surface crack length ($2a$) into the specimen width ($w$) at the cross section of the hole-type notch. The total crack length is a summation of the hole diameter and the crack lengths extending radially from each side of the hole perpendicular to the applied stress. The raw data were least-squares fitted to produce best-fit smooth curves for use in calculating fatigue crack growth rates. The corrections of the raw data by these manipulations were slight. At selected values of cycles, the equations for the smooth curves were differentiated to obtain $da/dN$, the fatigue crack growth rates.

For the conditions of these tests where there was a substantial amount of gross plastic strain, it appeared reasonable to assume that the growth of the fatigue cracks was governed primarily by the applied plastic strain and not by the stress field at the crack tip, as required by the linear elastic fracture mechanics criterion. The correlation of the crack growth data on the basis

(*Continued on page* 234-s)

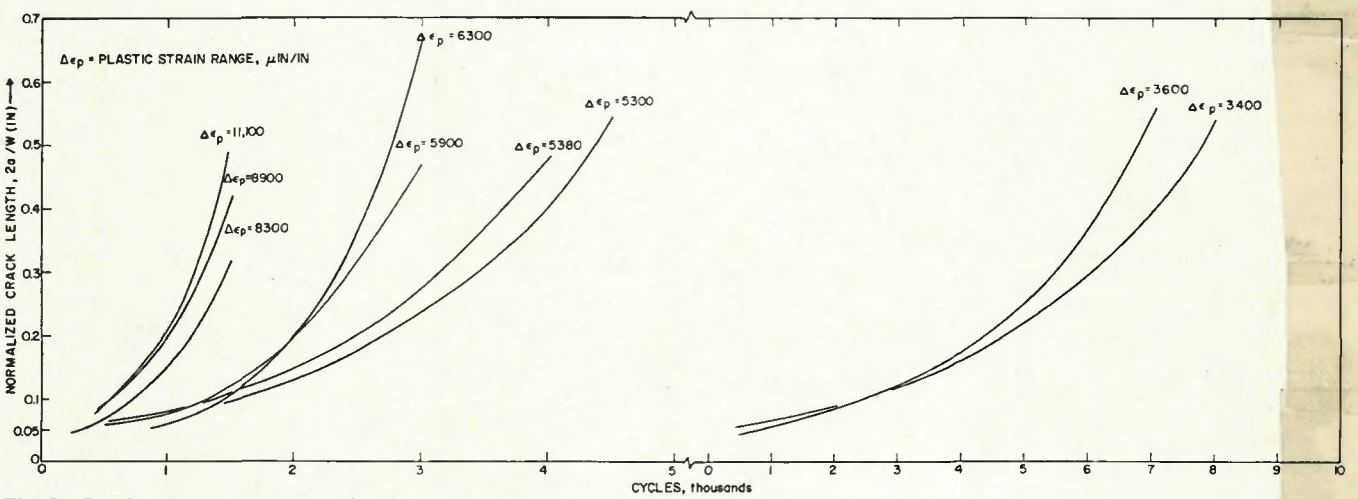


Fig. 2—Crack growth curves for Zircaloy weld metal

fillet welds loaded in shear are markedly dependent upon the orientation of the weld with respect to the line of action of the load. Welds placed parallel to the direction of the load have the lowest strength and highest ductility.

2. Fillet welds loaded in shear do not exhibit any well-defined yield point.

3. The load-deformation response of fillet welds cannot be generally represented as elastic or elastic-perfectly plastic. Mathematical expressions have been presented for all values of weld inclination to direction of applied load.

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# Technical Note: Fatigue Crack Propagation in Zircaloy-2 Weld Metal

Rotate in sync. w/arc pulses

(*Continued from page* 230-s)

of a plastic strain parameter would then be appropriate. Such a correlation has been made and the results are shown in Fig. 3. The growth rate was found to be proportional to the approximate second power of this parameter, $\Delta\epsilon_p\sqrt{a}$, over two decades ($10^{-6}$ to $10^{-4}$ in cycle) of growth rate. The data presented are from 11 specimens with surface plastic strain ranges varying from 3,400 $\mu$in./in. to 11,100 $\mu$in./in. The best-fit curve has a slope of 1.70, and the relationship which holds is:

$$da/dN = C(\Delta\epsilon_p\sqrt{a})^{1.70}$$

where $C$ = constant $\approx$ 3.3; $\Delta\epsilon_p$ = plastic strain range;* $a$ = half-crack length at specimen surface; $N$ = number of cycles.

The good agreement of the data with this plastic strain range crack growth parameter is encouraging, especially in relation to the results of Boettner et al,[6] who obtained a nearly identical correlation on axially cycled OFHC copper using striation markings to delineate crack growth. Recent additional work by this author on the fatigue of Zircaloy wrought material under completely reversed axial strain cycling in the high strain regime shows continuing correlation with this plastic strain parameter.

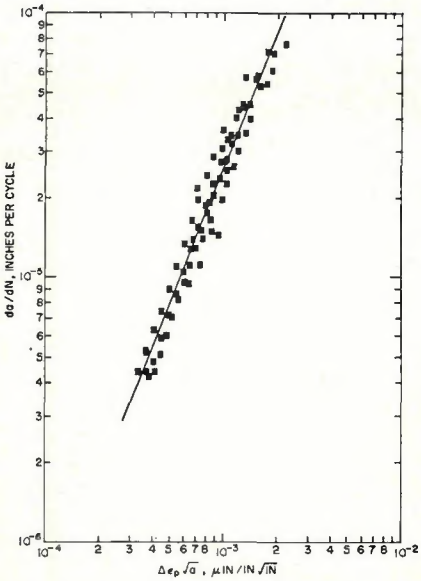


Fig. 3—Fatigue crack growth correlation in Zircaloy weld metal

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* In this study, plastic strain range ($\Delta\epsilon_p$) was approximated by subtracting twice the static yield strain ($\epsilon_e$), determined from a monotonic stress-strain curve, from the applied total strain range ($\Delta\epsilon_T$), a measured quantity. Use was made of the monotonic stress-strain curve because no cyclic stress-strain relationship could accurately be obtained from the load-strain fatigue data gathered during testing. This is due to the bending mode of loading, which causes a non-uniform stress distribution. This approach was considered valid because no cyclic hardening or softening was detectable within the accuracy of the laboratory measurements from the early life load records. In addition, the monotonic stress-strain curves of this material agrees well with the wrought Zircaloy cyclic stress-strain curves reported by O'Donnell and Langer.[4]